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EVALUATION OF A SPACECRAFT NITROGEN GENERATOR

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FINAL REPORT

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R.D. Marshall, M.K. Lee
and F.H. Schubert

April, 1978

Prepared Under Contract NAS2-8732

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Life Systems, Inc.
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AMES RESEARCH CENTER
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FOREWORD

The development work described herein was conducted by Life Systems, Inc. during the period February, 1976 to April, 1977. The Program Manager was Richard D. Marshall. Support was provided as follows:

Personnel	Area(s) of Responsibility
Myon K. Lee, PhD	NGM Testing and Analytical Support
Daniel C. Walters	NGM Mechanical Design and Fabrication
J. David Powell	Electrical Hardware Design
James Y. Yeh, PhD	Control Software Design
Franz H. Schubert	System Design Support
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The Contract Technical Monitor was P. D. Quattrone, Chief, Advanced Life Support Project Office, NASA Ames Research Center, Moffett Field, California.

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LIST OF ACRONYMS

ARS	Air Revitalization System
C/M I	Control/Monitor Instrumentation
CRS	CO_2 Reduction Subsystem
EC/LSS	Environmental Control/Life Support Subsystem
FMEA	Failure Modes and Effects Analysis
NGM	Nitrogen Generation Module
NGS	Nitrogen Generation System
NSS	Nitrogen Supply Subsystem
OGS	Oxygen Generation Subsystem
SPFA	Single Point Failure Analysis
TSA	Test Support Accessories

SUMMARY

A research and development program was successfully completed at Life Systems, Inc. towards the development of a method of generating nitrogen for cabin leakage makeup aboard space vehicles. The nitrogen generation concept uses liquid hydrazine as the stored form of nitrogen. This reduces tankage and expendables weight associated with high pressure gaseous and cryogenic liquid nitrogen storage. The hydrazine is catalytically dissociated to yield a mixture of nitrogen and hydrogen. The latter is separated to provide the makeup nitrogen. The hydrogen will be used in the reduction of metabolic carbon dioxide.

The development of a seven-stage Nitrogen Generation Module has been completed. The design successfully integrates a hydrazine catalytic dissociator, three ammonia dissociators and three palladium/silver hydrogen separators. Alternate ammonia dissociation and hydrogen separation stages are used to remove hydrogen and ammonia formed in the dissociation of hydrazine and results in negligible ammonia and hydrogen concentrations in the product nitrogen stream. The Nitrogen Generation Module has been designed to generate 3.6 kg/d (8.0 lb/d) of high-purity nitrogen containing less than or equal to 0.2% hydrogen and 50 ppm ammonia. The dissociation and separation stages are packaged as a single unit to minimize heat rejection to ambient since both operate at elevated temperatures. The single package concept allows the heat generated during the dissociation of hydrazine to reduce the heater power required to maintain the Nitrogen Generation Module at temperature.

The development of a Nitrogen Supply Subsystem as an integratable subsystem for a central spacecraft Air Revitalization System has been completed. The subsystem consists of the hydrazine storage and feed mechanism, the Nitrogen Generation Module, the peripheral mechanical and electrical components required to control and monitor subsystem performance and the instrumentation required to interface with other subsystems of an Air Revitalization System. The Nitrogen Supply Subsystem has been designed to deliver nitrogen at a rate of 3.6 kg/d (8.0 lb/d) at pressures of 1725 kPa (250 psia) or less. The subsystem recovers 84% (with the remaining vented to vacuum) of the hydrogen contained in the feed hydrazine stream and delivers 0.44 kg/d (0.96 lb/d) of hydrogen for use in the reduction of carbon dioxide.

The activities demonstrated hardware can be developed to meet future central Air Revitalization System requirements. Future activities are required to experimentally characterize the hardware developed and establish the performance level and data base for flight hardware designs. The data gathered will also reflect the subsystem's maturity level for flight application.

INTRODUCTION

Future long-term manned spacecraft missions will utilize an atmosphere of nitrogen (N_2) and oxygen (O_2). Space vehicle gas leakage and cabin depressurization requirements necessitate on-board storage of the primary cabin atmospheric constituents, N_2 and O_2. The N_2 component of air can be stored as liquid hydrazine (N_2H_4) and the N_2H_4 catalytically dissociated to an N_2 and hydrogen (H_2) mixture. The N_2/H_2 mixture is then separated to yield the

makeup N_2. The byproduct H_2 is used in the reduction of metabolically generated carbon dioxide (CO_2).

A research and development program has been established to evolve the capability for generating N_2 for cabin leakage makeup aboard a space vehicle of mission duration requiring regenerative methods for reprocessing the crew's metabolic products. The development program is focused on the Nitrogen Supply Subsystem (NSS) for a regenerative Environmental Control/Life Support Subsystem (EC/LSS).

Background

During the previous program[1] Life Systems, Inc. (LSI) identified two attractive N_2 generation systems based on the catalytic dissociation of N_2H_4. In the first system, liquid N_2H_4 is catalytically dissociated to yield an N_2/H_2 gas mixture. Separation of the gas mixture to yield N_2 and byproduct H_2 is accomplished using a Polymer-Electrochemical N_2/H_2 Separator.[2,3] In the second system, the N_2/H_2 product gas from the dissociator is separated in a Palladium/Silver (Pd/Ag) N_2/H_2 Separator.

The program culminated in the successful design, fabrication and testing of an N_2H_4 Catalytic Dissociator, a Polymer Electrochemical N_2/H_2 Separator and a two-stage Pd/Ag N_2/H_2 Separator. Based on the results of this program it was recommended that a N_2 Generation System (NGS), and subsequently an NSS, be developed based on N_2H_4 catalytic dissociation and the Pd/Ag method of H_2 separation.

Program Objectives

The objectives of the present program were to develop and evaluate:

1. a laboratory breadboard of an NGS based on the catalytic dissociation of N_2H_4,
2. a Nitrogen Generation Module (NGM) to reduce ammonia (NH_3) concentrations in the product N_2, and
3. an engineering model of the NSS which incorporates the NGM and is integratable within an Air Revitalization System (ARS).

The NGS consists of the N_2H_4 Catalytic Dissociator and the two-stage Pd/Ag Separator developed on the previous contract (NAS2-7057). The NGM incorporates a staging concept and combines all dissociation and separation stages into a single unit to lower NH_3 concentration in the product N_2. The NSS incorporates the N_2H_4 storage and feed mechanism, the NGM and the advanced instrumentation required to control and monitor NSS performance, and to interface with other ARS subsystems and controls.

The NGS development activities completed were summarized in a separate report.[4] The present report summarizes the NGM and NSS development activities completed.

(1) All references cited are listed at the end of this report.

NITROGEN GENERATION MODULE DEVELOPMENT

The NGM is the major component in an NSS based on the catalytic dissociation of liquid N_2H_4 and subsequent separation of the product gases into N_2 and H_2. The NGM combines all catalytic dissociation and subsequent Pd/Ag H_2 separation stages into a single unit. The objective of the initial development activities was to develop the initial NGM hardware required to (a) demonstrate and verify the staging concept and the single unit NGM design, and (b) experimentally generate a technology base that can be used to optimize subsequent advanced NGM designs. Emphasis in these development activities, therefore, was placed on developing an NGM that could be used as a test bed to generate necessary design data. Only secondary emphasis was placed on minimizing NGM weight. The following sections review the NGM design concept, operation and summarize the hardware fabricated. The initial test results obtained on the H_2 separation, NH_3 dissociation and N_2H_4 dissociation stages are also discussed.

Design Description

The function of the NGM is to generate N_2 and byproduct H_2 from liquid N_2H_4. The NGM consists of alternate catalytic dissociation and Pd/Ag separation stages configured to give high purity N_2 and H_2. The dissociator and separator stages are packaged as a single unit to minimize heat rejection to ambient since both operate at elevated temperatures. The single package concept allows the heat generated during the dissociation of N_2H_4 to reduce the heater power required to maintain the NGM at operating temperature.

Concept Description

A block diagram showing the staging concept is presented in Figure 1. The NGM consists of one N_2H_4 dissociation stage, three NH_3 dissociation stages and three Pd/Ag separation stages. The N_2H_4 feed/N_2 product stream flows in series from stage to stage. The projected gas concentrations following each dissociation and H_2 separation stage are presented in the block diagram to demonstrate the method of obtaining low NH_3 and H_2 concentrations.

Hydrazine is dissociated in the first stage via the following reactions:[5]

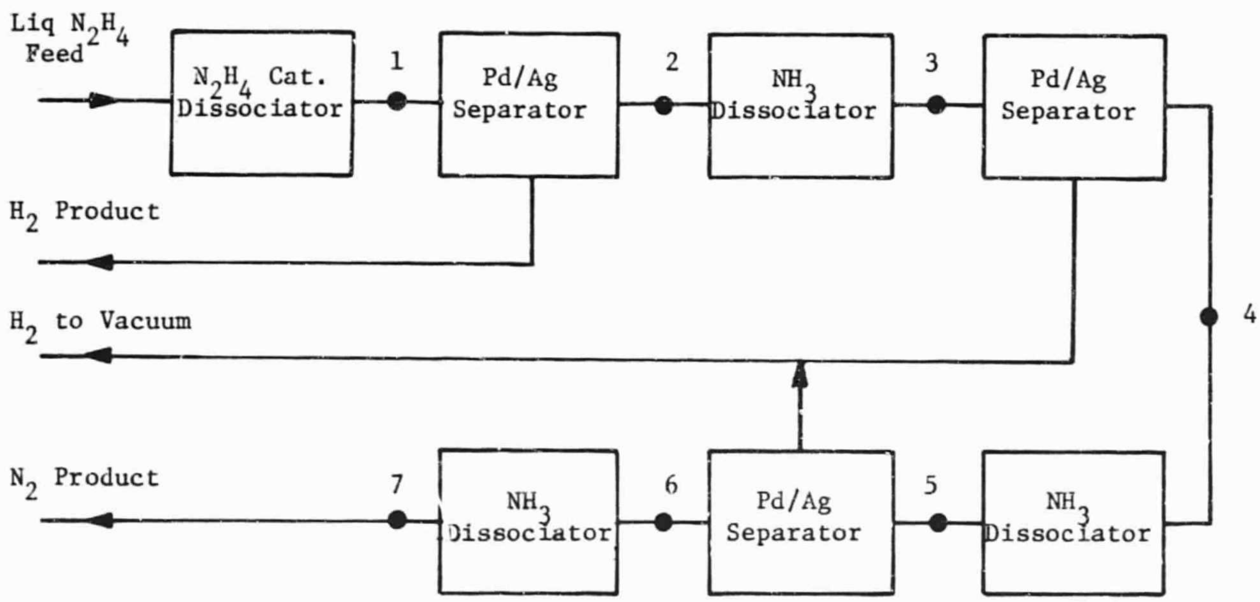
$$N_2H_4 = 1/3\ N_2 + 4/3\ NH_3 \tag{1}$$

$$\underline{4/3\ NH_3 = 2/3\ N_2 + 2H_2} \tag{2}$$

$$N_2H_4 = N_2 + 2H_2 \tag{3}$$

All the N_2H_4 is dissociated in this initial stage. Not all of the NH_3 formed by equation 1, however, is dissociated in the N_2H_4 dissociation stage.

The N_2/H_2 and unreacted NH_3 from the first stage enters the first Pd/Ag separation stage. Most (90%) of the H_2 entering this stage is removed and collected at 172 kPa (25 psia) for use in the CO_2 Reduction Subsystem (CRS). The N_2 product gas from the first separation stage is then manifolded to the first NH_3 dissociation stage. The high NH_3 and N_2 concentration entering the dissociator favors further NH_3 dissociation and the formation of more N_2 and H_2 (equation 2).



Stream	% N_2	% H_2	% NH_3	Eff. %	Temp. K (F)
1	32.8	64.0	3.2	93	1000 (1340)
2	77.3	15.1	7.6	90	644 (700)
3	75.8	22.8	1.4	80	811 (1000)
4	96.7	1.5	1.8	95	644 (700)
5	95.9	4.0	0.09	95	811 (1000)
6	99.8	0.08	0.09	98	644 (700)
7	99.78	0.2	19 ppm	98	811 (1000)

FIGURE 1 NGM STAGING CONCEPT BLOCK DIAGRAM

Alternate H_2 separation and NH_3 dissociation stages are used to attain the final N_2 product purity. The H_2 removed in the remaining H_2 separation stages is vented to space vacuum and is therefore not available for use in the CRS. The H_2 separation to vacuum is required to attain the low H_2 concentration required in the product N_2.

Design Specifications

The NGM design specifications are presented in Table 1. The NGM was sized to deliver 3.63 kg/d (8.00 lb/d) of N_2 and 0.44 kg/d (0.96 lb/d) of H_2. The NH_3 concentration in the product N_2 is of prime concern in the NGM design since less than 50 ppm is required to satisfy contamination requirements for direct utilization of N_2 in a spacecraft cabin atmosphere. The requirement for less than or equal to 0.2% H_2 in the product N_2 is not as critical since lower H_2 concentrations have been demonstrated previously.[4] A final or cleanup H_2 separation stage could be added to any prototype/flight NGM design if required.

Operation

Figure 2 is a functional schematic of the NGM showing the orientation of the individual stages. The NGM performs three functions; N_2H_4 dissociation, NH_3 dissociation and H_2 separation. The temperatures of the dissociation stages and separation stages are controlled separately using two sets of heaters. Coolant N_2 is provided between the two temperature zones in the event cooling is required to control the two zones independently.

Hydrazine Dissociation

Hydrazine dissociation takes place in the center cavity of the NGM. Liquid N_2H_4 at a pressure of approximately 2070 kPa (300 psia) is injected into the dissociator through a capillary orifice in the header assembly. The diameter of the capillary opening is smaller than the quenching diameter for N_2H_4 to prevent propagation of the dissociation reaction back to the feed tanks. In the feed orifice N_2H_4 is taken from a liquid at ambient temperature to a vapor slightly above the boiling point of N_2H_4 at the operating pressure.

Hydrazine vapor enters the central dissociator tube at an elevated temperature and dissociates autocatalytically. The central feed tube is packed with 10 to 20 mesh tungsten chips to allow heat to transfer to the gas phase which promotes the autocatalytic reaction. A platinum (Pt) screen is located at the end of the central feed tube to insure that any undissociated N_2H_4 reacts prior to entering the packed catalyst bed in the concentric annular housing.

At the end of the central tube the flow pattern of the product gases is reversed in direction. The product gases flow in the annular housing concentric with the central tube and exit at the hottest zone in the reactor. The decomposition of NH_3 into N_2 and H_2 (equation 2) is favored kinetically and thermodynamically at higher temperatures.[6] The hairpin-type reactor design will therefore result in higher NH_3 conversion efficiencies in the N_2H_4 dissociation stage.

TABLE 1 NGM DESIGN SPECIFICATIONS

N_2H_4 Feed Rate, kg/d (lb/day)	4.15 (9.14)
N_2 Generation Rate, kg/d (lb/day)	3.63 (8.00)
H_2 Generation Rate, kg/d (lb/day)	0.44 (0.96)
N_2 Product Composition, Volume %	
H_2	≤ 0.2
NH_3	$\leq 5 \times 10^{-3}$
Water[(a)]	≤ 0.1
H_2 Byproduct Purity, Volume %	>99.9
Surface Temperature Guidelines, K (F)	≤ 322 (120)

(a) The water concentration in the N_2 product stream is caused by the small amount of water present in the N_2H_4 feed stream.

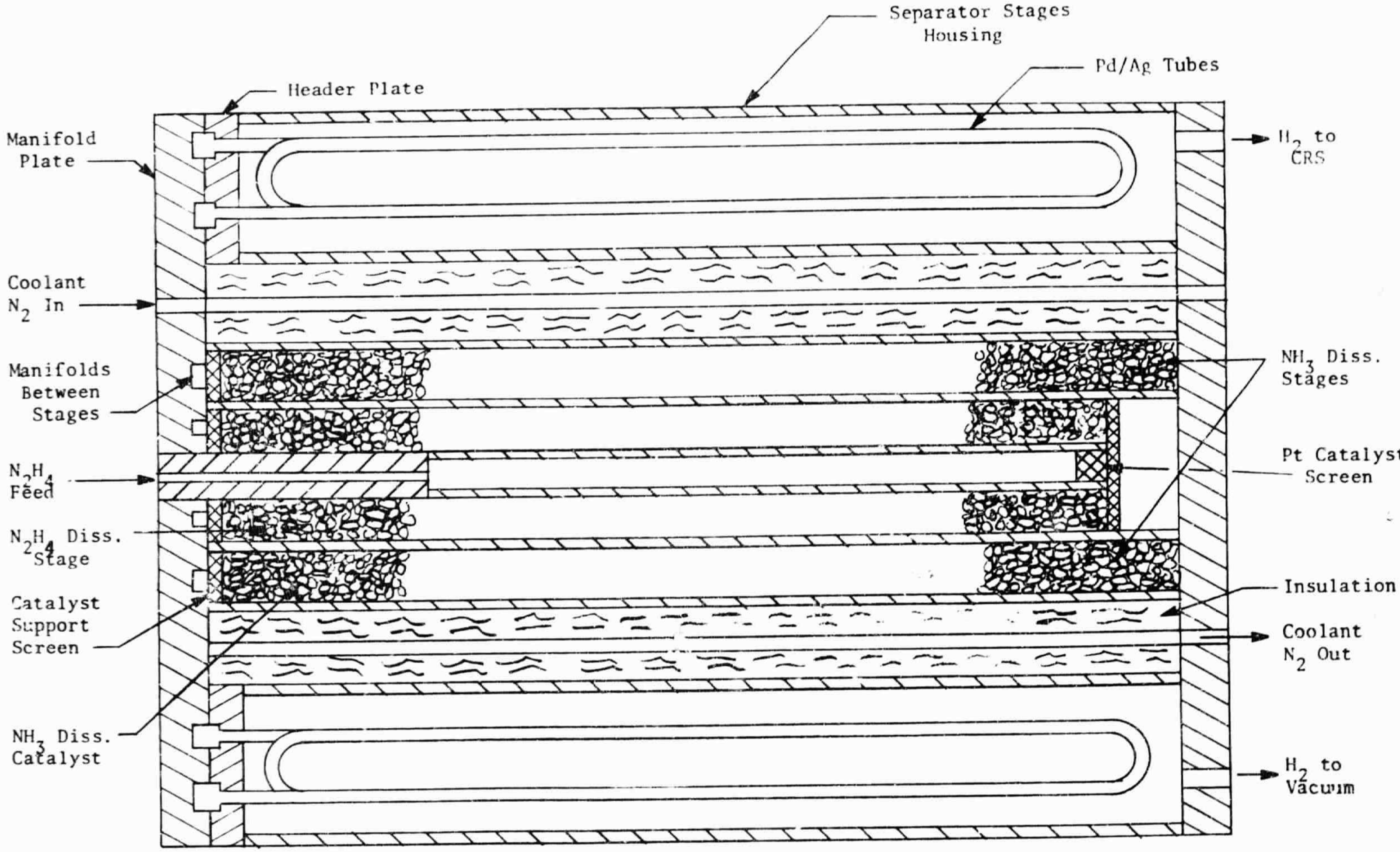


FIGURE 2 NGM FUNCTIONAL SCHEMATIC

Tungsten catalyst retaining screens are used to prevent catalyst particles from being removed by the product gases. The product gas from the N_2H_4 dissociation stage is manifolded to the first Pd/Ag separation stage.

Ammonia Dissociation

The three NH_3 dissociation stages are located in the central NGM core around the outside of the N_2H_4 dissociation stage. The product N_2 gas stream, enriched in N_2 and NH_3 after passing through an H_2 separation stage, is fed into an NH_3 dissociation stage at the same end of the NGM as the N_2H_4 feed. The product gas passes through the packed catalyst bed traveling the length of the dissociator core. At the end of the first catalyst bed the gases are manifolded to the second portion of the catalyst bed in the dissociation stage. The product gas then travels back the length of the reactor core and exits at the same end of the reactor as the feed stream. Each NH_3 dissociation stage, therefore, consists of two side-by-side tubes packed with catalyst.

Pd/Ag Separation

The three H_2 separation stages are located around the outside of the NGM. The Pd/Ag tubes are connected to a donut-shaped header plate and are thermally isolated from the central NGM core where N_2H_4 and NH_3 dissociation takes place. The reason for the thermal isolation is the difference in operating temperatures. The H_2 separation stages operate at 644 K (700 F) and the dissociator core is maintained at 1000 K (1340 F).

The H_2 separation stages are connected to the main manifold plate which manifolds the process gases between the H_2 separation and the dissociation stages. The N_2/H_2 mixture from a dissociation stage enters the inside ends (i.e., closest to the center of the NGM) of Pd/Ag tubes in the stage. The process gas passes through all of the Pd/Ag tubes in each individual stage in parallel. The H_2-depleted gas stream from an H_2 separation stage is then manifolded from the outside ends of the tubes to the next NH_3 dissociation stage.

In the first H_2 separation stage, H_2 is collected at less than or equal to 172 kPa (25 psia) for use in the CRS. The H_2 removed in the second and third H_2 separation stages exhausts the NGM through a common manifold and is vented to vacuum.

Temperature control of the Pd/Ag separation stages is provided through metal fins which connect the outside and inside concentric cylinders which form the housing for the separation stages. Band heaters located on the outside wall are able to transmit heat to the inside surface through these fins, thereby keeping the Pd/Ag tubes at a constant temperature.

Operating Conditions

Table 2 gives the projected steady-state operating conditions for the NGM. Only dissociation stage and separation stage temperatures are controlled using three cartridge heaters located in the dissociator core and five band heaters located around the outside of the H_2 separator housing. Thermocouples located

TABLE 2 NGM NOMINAL OPERATING CONDITIONS

Catalytic Dissociator Temperature, K (F)	1000 (1340)
Pd/Ag Separator Temperature, K (F)	644 (700)
N_2H_4 Feed	
Source	Liquid N_2H_4
N_2H_4 Flow Rate, kg/d (lb/d)	4.15 (9.14)
cm^3/min	2.9
Composition, Weight %	
N_2H_4	99.5 to 100
Water	0 to 0.5
Temperature, K (F)	291 to 297 (65 to 75)
Pressure, kPa (psia)	1794 (260)
N_2 Product	
Flow Rate, kg/d (lb/d)	3.63 (8.0)
dm^3/min (scfm)	2.2 (0.078)
Composition, Volume %	
H_2	0.2
NH_3	1.9×10^{-3}
Water	<0.1
Temperature, K (F)	644 (700)
Pressure, kPa (psia)	1725 (250)
H_2 Byproduct	
Flow Rate, kg/d (lb/d)	0.44 (0.96)
dm^3/min (scfm)	3.6 (0.13)
Purity, Volume %	99.9999 to 100
Temperature, K (F)	644 (700)
Pressure, kPa (psia)	173 (25)
H_2 Vented	
Flow Rate, kg/d (lb/d)	0.08 (0.18)
dm^3/min (scfm)	0.68 (0.024)
Temperature, K (F)	644 (700)
Pressure, Pa (mm Hg)	0 to 1334 (0 to 10)

continued-

Table 2 - continued

Coolant Supply	
Type	Ambient Air, or N_2
Temperature, K (F)	291 to 297 (65 to 75)
Flow Rate, dm^3/min (scfm)	28 (1)
Cabin Environment Data	
Operational Gravity, m/s^2 (G)	0 to 9.8 (0 to 1.0)
Total Pressure, kPa (psia)	101.4 (14.7)
O_2 Partial Pressure, kPa (psia)	21.4 (3.1)
Diluent	N_2
H_2 Concentration, Volume %	0.2
NH_3 Concentration, Volume %	5.0×10^{-5}
Temperature, K (F)	291 to 297 (65 to 75)

within the NGM are used to provide closed-loop temperature feedback control. The central dissociator core is controlled at 1000 K (1340 F) and the Pd/Ag Separator tubes are controlled at 644 K (700 F). In addition to the heaters, a port for N_2 coolant gas is provided between the central dissociator core and the Pd/Ag separator stages in the event that the Pd/Ag tubes should start to overheat due to the heat generation in the central dissociator core.

Hardware Description

Photographs of the assembled and disassembl d NGM mockup are presented in Figures 3 and 4, respectively. Figure 5 shows the actual assembled NGM hardware with the experimental manifold endplate. The NGM consists of ten major subassemblies/components. These major subassemblies/components are summarized in Table 3. The NGM hardware description is summarized in the following sections through a discussion of the individual design considerations.

Operational Flexibility

Since the NGM will be used to generate performance and design data for future NGM designs, maximum flexibility in the design and operation of the NGM was required. A maintainable design consisting of ten major subassemblies was selected. Individual stage testing as well as integrated NGM stage testing was accomplished by fabricating an experimental manifold endplate having inlet and outlet process gas ports for two of the separator stages, one NH_3 dissociation stage and the N_2H_4 dissociator. This experimental manifold was used during the individual stage checkout tests conducted as part of the present program.

The capability to monitor individual stage performance and temperature distribution profile data, and to individually control separator and dissociator stage temperatures was incorporated into the design to provide testing flexibility. Gas sample taps between each stage were incorporated to allow a sample to be analyzed thereby quantifying individual stage performance during integrated operation. The NGM temperature distribution profile is monitored through the incorporation of 18 thermocouples which provide for both radial and axial temperature profiles. Separate temperature control of the dissociation stages and separator stages is provided through heaters which are connected to a feedback temperature control. An N_2 cooling source is also provided should it be necessary for temperature control.

One additional design flexibility was required in the N_2H_4 dissociation stage. The NGM was designed to incorporate different N_2H_4 dissociator designs. The N_2H_4 dissociator can be maintained from the endplate. The N_2H_4 dissociator threads into the endplate and sealing is provided using a C-ring.

Maintainability

Maintainability is not a requirement of a flight version NGM. Maintainability, however, for the NGM fabricated for development testing under the present effort was required for testing flexibility. Operation at elevated temperatures and pressures, and the dimensional tolerances required for adequate sealing make disassembly and maintainability difficult. Operation at elevated tempera-

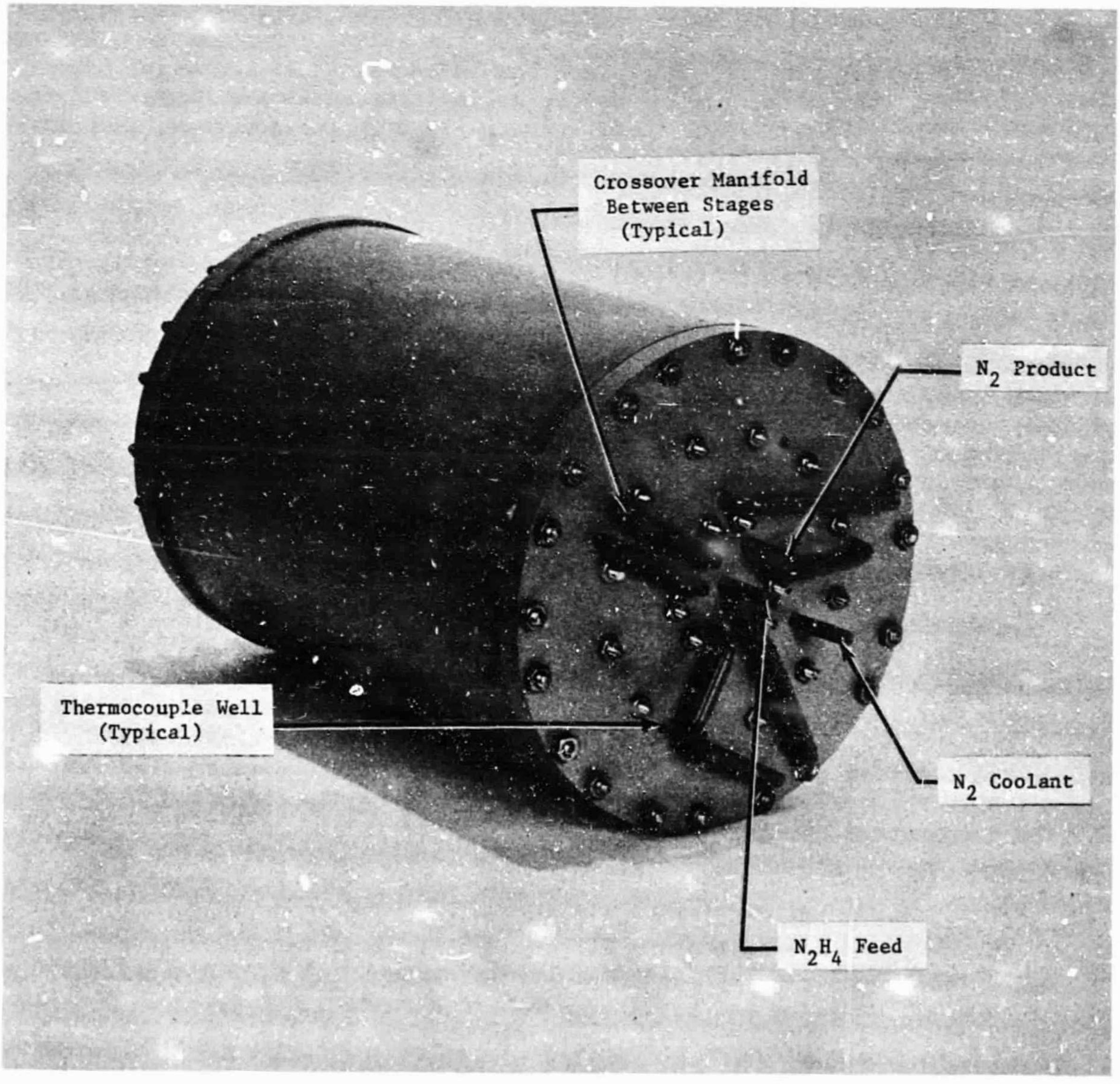


FIGURE 3 NITROGEN GENERATION MODULE MOCKUP (ASSEMBLED)

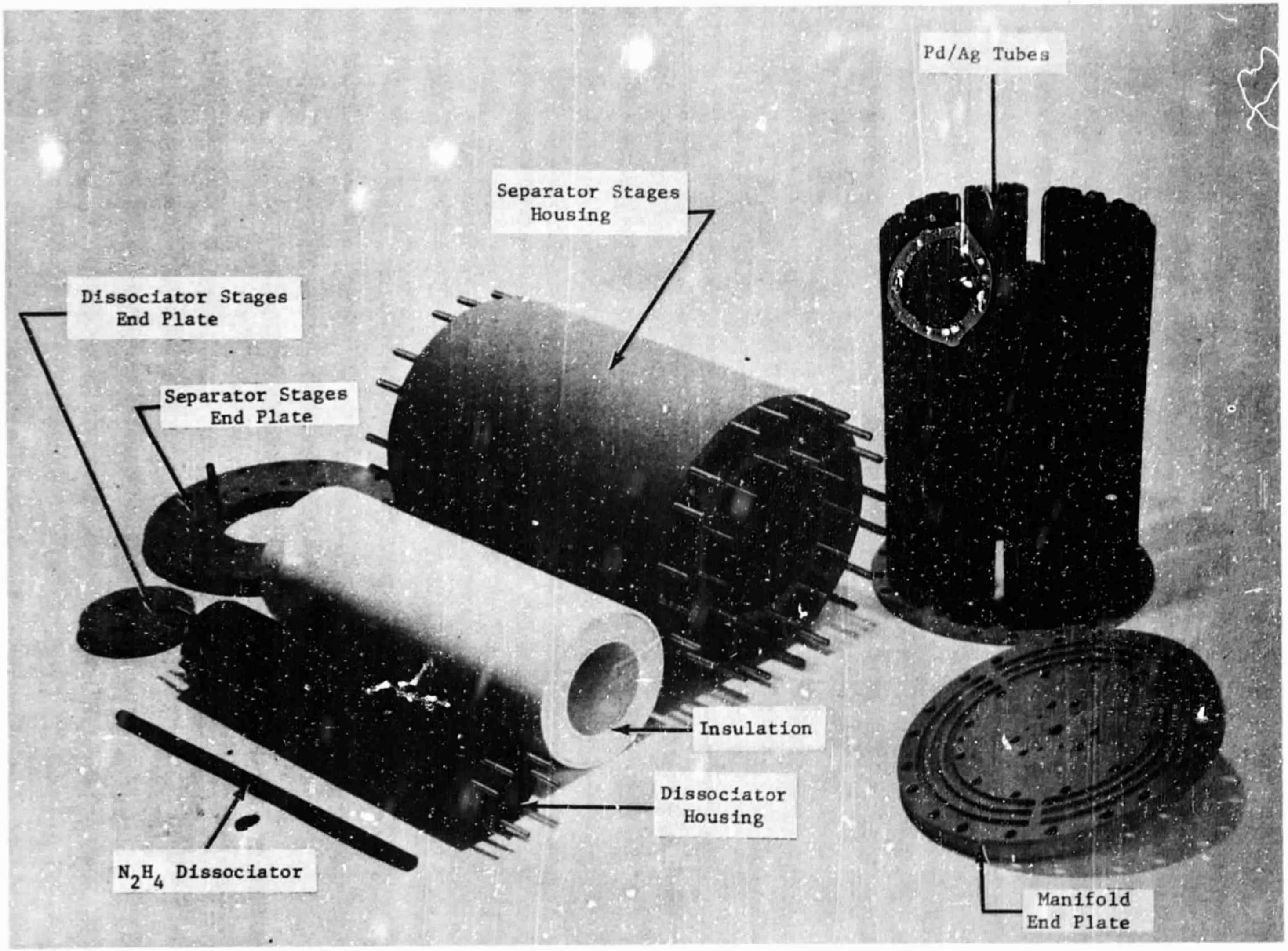


FIGURE 4 NITROGEN GENERATION MODULE MOCKUP (DISASSEMBLED)

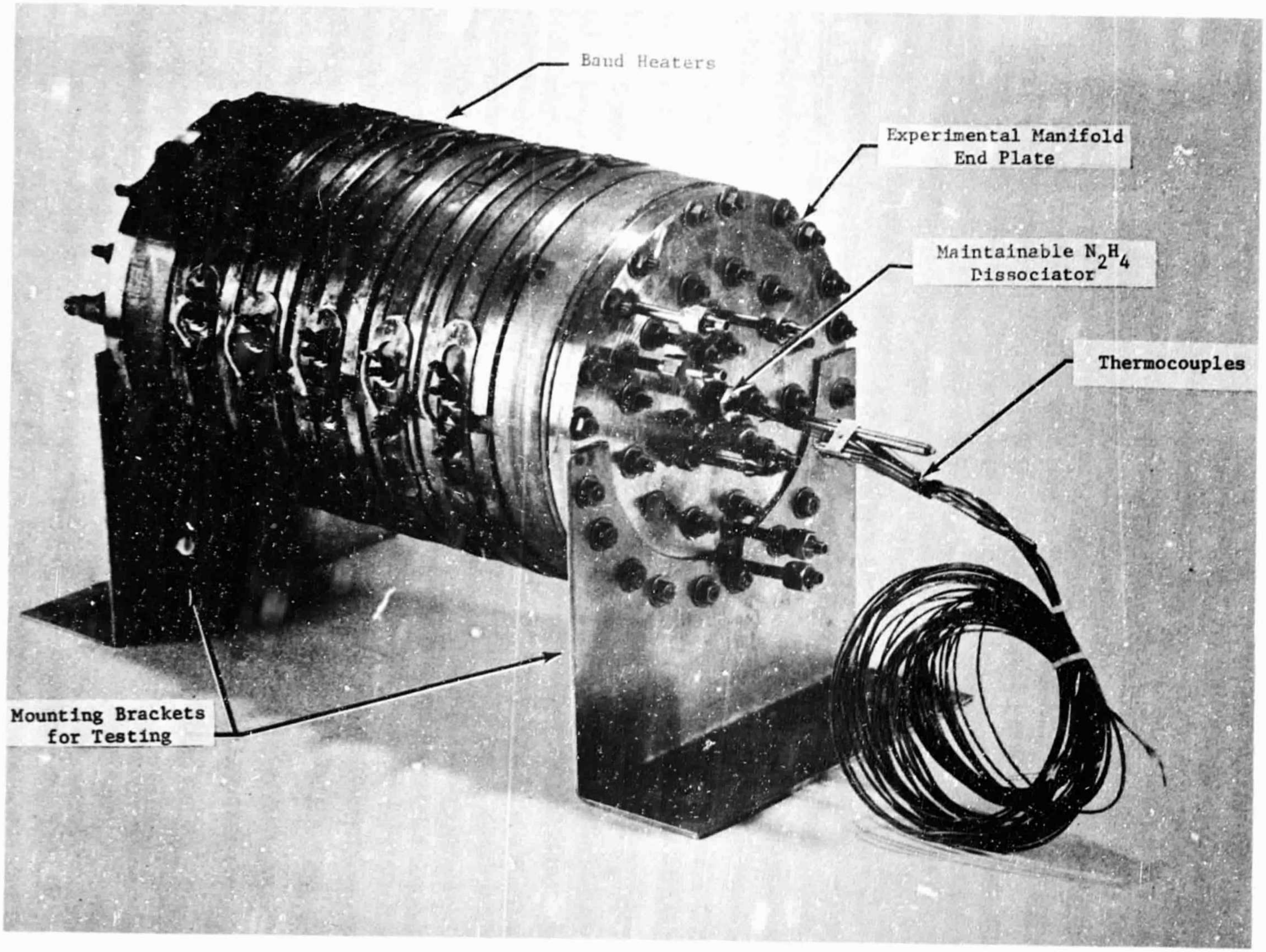


FIGURE 5 NITROGEN GENERATION MODULE

TABLE 3 NGM SUBASSEMBLIES/COMPONENTS

Subassembly/Component	Number Required
Housing, Separation Stages	1
Header Plate (with Pd/Ag Tubes)	1
End Plate, Manifold	1
End Plate, Separation Stages	1
End Plate, Dissociation Stages	1
Dissociator, N_2H_4	1
Housing, Dissociation Stages	1
Heaters, Cartridge	3
Heaters, Band	5
Insulation, Internal	1

tures causes the metal surfaces to adhere to each other through oxidation and scaling. Operation at elevated pressures and the large surface area required for sealing cause the sealing force required to be high.

The NGM was divided into ten major subassemblies and components for disassembly during maintenance. Sealing between the subassemblies is provided by graphite gaskets. Studs, which are screwed into the dissociator and separator stages housings, and nuts are used to hold these subassemblies together and provide the sealing force required.

Temperature Control/Distribution

Heat is (a) generated in the N_2H_4 dissociation process, (b) required for the NH_3 dissociation process and (c) lost to ambient since the surface of the NGM (the separator stages) is at 644 K (700 F). The NGM has two distinct temperature zones. The Pd/Ag separator stages operate at 644 ±28 K (700 ±50 F). The separation process is favored by higher temperatures but temperatures above 700 K (800 F) can decrease the reliability and life of the Pd/Ag tubes. The NH_3 dissociation stages requires temperatures greater than or equal to 811 K (1,000 F). The center of the dissociator housing (i.e., the N_2H_4 dissociation stage) operates at approximately 1,000 K (1340 F). The temperature then decreases to 811 K (1000 F) at the surface of the dissociator core.

Thermal control of the two separate zones is provided by three cartridge heaters located in the dissociator core and five band heaters located around the outside of the separator stages housing. Separate feedback temperature control circuits are used to control the two separate temperature zones. Between the two zones, insulation is provided because of the large temperature difference. A cooling gas port is also provided between the dissociator core and the separator housing to prevent excessive temperatures. The objective, of course, is to minimize heater power and, with development time, eliminate the need for heater power. A passive thermal design is desired in which all heat required (that which is lost to ambient) is generated by the N_2H_4 dissociation process and each temperature zone is maintained without controls.

Since the dissociator core is made from a single piece of metal, minimum thermal gradients occur. The temperature profile throughout the dissociator core is fairly evenly distributed being hottest in the center and cooling to the surface. The separator stages housing however is made of two concentric cylinders which are connected by fins which separate the individual stages. These fins not only provide stage separation for the collected H_2 but also allow heat to conduct between the two cylinders. The band heaters are located on the outside surface of the NGM. Should heat be required to maintain the temperature of the separator stages, it must conduct through these fins to the inner surface. The fins provided in the current design maintain the temperature of the separator stages at all points to within ±28 K (50 F).

The two separate temperature zones cause one additional design problem; thermal expansion of the metals involved when controlling the different temperatures could cause sealing problems. The staging process alternately uses separator and dissociator stages and therefore a manifold technique is still required to connect the two temperature zones. The present design accommodates

the different thermal expansion rates by connecting the dissociator and separator stages to a manifold end plate on one end, but using separate end plates on the other end. The separate end plates allow the hotter dissociator core to expand more than the separation stages thereby eliminating sealing and possible mechanical failure problems.

Sealing

Sealing between the various NGM stages was necessitated by the maintainability requirements. The sealing requirements for the NGM are differential pressures of 1725 kPa (250 psia) to vacuum, compatibility with elevated temperatures (up to 1000 K (1340 F)), compatibility with a corrosive NH_3, H_2 and N_2 atmosphere and irregular (non-circular) sealing surface geometries. These sealing criteria limited the selection of a sealing method to customized metal C-rings or O-rings, or graphite gaskets. Subsequent discussions with possible vendors indicated that C-rings could not be configured to the desired geometry. O-rings could be configured, however, they would be expensive and have to be welded together to make the geometric requirements. The weak point in the O-ring would therefore be the point at which the weld occurred and the chance of sealing success, therefore, was judged low using the metal O-rings. Graphite gaskets have been used for high-temperature sealing applications and meet the temperature and compatibility requirements. Vendor data indicated that a flat graphite gasket would be capable of handling the sealing requirements without problems. The graphite gasket sealing technique was therefore selected. In addition, the graphite gaskets were supposed to be reusable thereby reducing the number (and cost) required.

After fabrication of the NGM and the graphite gaskets, initial sealing tests uncovered several problems with the graphite gasket sealing material. Design data offered by the vendor indicated that there would be no cold flow problems using the graphite gaskets. Further investigation, however, showed that cold flow problems did occur. Minor gas leakage was also uncovered and appeared to be diffusion through the graphite gasket material itself. The bolt forces used to seal the graphite material were set as specified by the vendor and were even increased by 50% without success. Upon disassembly of the NGM it was discovered that the graphite gasket material was not reusable as originally thought. The graphite gasket material strongly adheres to the metal surfaces in contact with it. Upon disassembly, the gasket adheres to both metal surfaces and is pulled apart making reuse impossible. A solution to the sealing problems encountered is required and has been recommended prior to extensive NGM development testing.

Materials of Construction

A detailed list of all NGM parts and their compatibility requirements (environment) was prepared prior to fabrication. The major materials considerations required for the NGM are compatibility with the process gas and operation at elevated temperatures. The thermal expansion properties of all materials were also considered. The primary materials compatibility problems faced were corrosion due to N_2H_4 and NH_3, nitrification and H_2 embrittlement. All materials used passed the required materials standards.

Manifolding Between Stages

All manifolding of the N_2 product gas stream between the various separation and dissociation stages was accomplished using a single manifold plate. This single plate at one end of the module helped eliminate thermal expansion problems caused by the different NGM temperature zones. All N_2 process gas streams therefore enter and leave a stage at the same end of the NGM. The H_2 by-product and vent to vacuum streams which do not require manifolding between stages are collected from the shell side of the separator stage housing at the opposite end of the NGM.

Interfaces

The NGM has five mechanical interfaces and two electrical interfaces. The mechanical interfaces are the N_2H_4 liquid feed stream, the N_2 product stream, the H_2 by-product, the H_2 vented to vacuum and the N_2 coolant supply. The electrical connections include power to the heaters and the temperature sensor connectors. The NGM contains eight temperature sensors; two are used for control and six are used for fault detection and isolation. The NGM also has provisions for an additional 10 thermocouples for temperature profile mapping during development testing.

NGM Test Facilities

The facilities used to test the NGM prior to integration with the NSS consisted of the breadboard NGS and its Test Support Accessories (TSA) and Control/Monitor Instrumentation (C/M I) developed under the initial phase of the contract.(4) The NGS, TSA and C/M I were modified to test the NGM.

Nitrogen Generation System (NGS) Hardware

The NGS schematic as modified for NGM testing is presented in Figure 6. Hydrazine is fed under pressure and at room temperature into the NGM through a pneumatic valve (PV1) and a flow meter (Q8). Porous, stainless steel filters (F1 and F2) are used to prevent the orifice (O1) from clogging by particles contained in the N_2H_4 feed or possible catalyst dust from the dissociator. The liquid N_2H_4 flow rate is controlled by manually adjusting the N_2H_4 feed pressure.

In the NGM, N_2H_4 decomposes spontaneously to NH_3, N_2 and H_2. The NH_3 formed is further dissociated over the catalyst bed of NH_3 dissociators to N_2 and H_2. Hydrogen is then separated from the product gas mixture as it flows through three Pd/Ag separators. Both the H_2 from the first separator and the N_2 product pass through heat exchangers HX1 and HX2, respectively to TSA for gas analysis and flow rate measurements. A cooling fin (B1) is used for HX1 while HX2 is cooled by natural connection. The H_2 stream from the second and last Pd/Ag separation stages is directly vented through the vacuum pump (P1).

For the single-stage checkout testing a calibration gas which simulated the gas composition of the feed stream was fed to the inlet of the stage being tested and the outlet was directly connected to the N_2 product line.

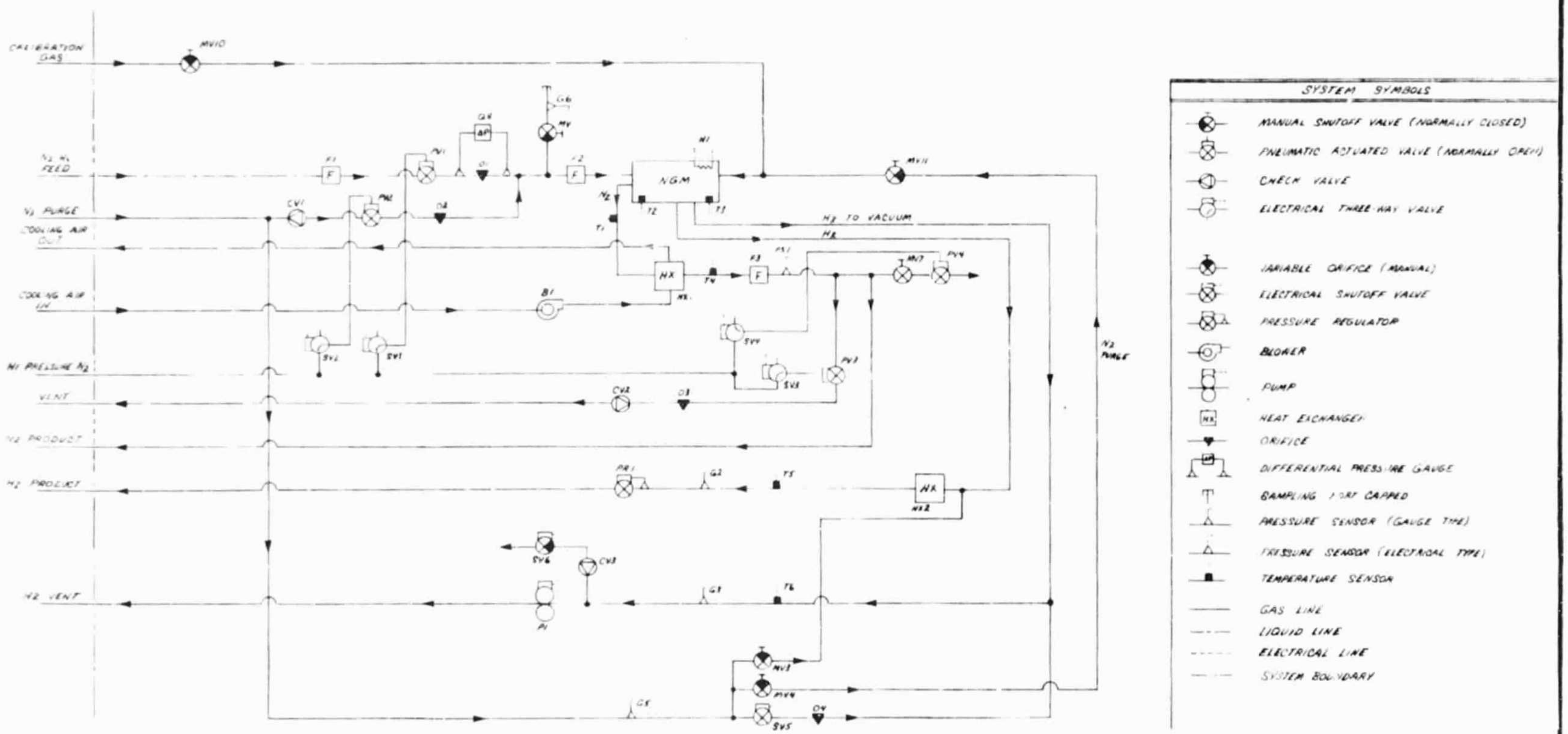


FIGURE 6 NGM TEST FACILITY

The system is equipped with a semiautomatic N_2 purge system which remains idle during normal operation. A shutdown initiates the automatic purging system installed in the N_2H_4 feed/N_2 product line and the H_2-to-vacuum line. Prior to startup these lines are manually purged to prevent ambient air from entering the system.

NGS Test Support Accessories (TSA)

The function of the TSA is to provide the NGS interfaces required to test the NGM. The TSA, schematically shown in Figure 7, provides: (1) N_2H_4 feed mechanism, (2) N_2H_4 storage, (3) process gas interfaces and (4) power supply.

Hydrazine Feed Mechanism. Hydrazine is fed by pressurizing the N_2H_4 feed tank to the pressure level that gives the required flow rate through an orifice (O1) located in the NGS. Each tank has a sufficient amount of N_2H_4 to operate at the flow rate equivalent to 3.63 kg/d (8.00 lb/d) of N_2 for one day. Valving is provided to allow uninterrupted operation of the NGS by refilling one tank while the other tank remains operative.

The N_2H_4 feed line to the NGS also contains a pneumatic valve (PV4) which closes when the NGS is shut off. This valve provides in line redundancy with its counterpart located in the NGS. This redundant valve insures fail-safe shutdown and shutoff of the N_2H_4 feed supply during NGS shutdown, even if one of the two valves should fail.

Hydrazine Storage. Hydrazine is stored in a separate drum. The individual N_2H_4 feed tanks in the TSA are refilled from the storage drum. During refill, one N_2H_4 feed tank is depressurized while the other tank continues to feed N_2H_4 to the NGS. The depressurized tank is then refilled by using pressure to transfer N_2H_4 from the storage drum to the feed tank. The overflow of N_2H_4 into the N_2H_4 water trap indicates that the tank is full. The refilled tank is then repressurized and can either be hooked back into the system in parallel with the other tank, or as is the case under normal operation, will be held in reserve until the other N_2H_4 tank is ready for refill.

Process Gas Interfaces. The TSA provides the process gas interfaces with the NGS. The five process gas interfaces are: (1) N_2 purge, (2) high pressure N_2, (3) process gas vent, (4) gas analysis test and (5) ambient air.

Bottled N_2 purge gas is supplied to the NGS at 310 kPa (45 psia). The purge gas is taken from the same source as the N_2 used to pressurize the N_2H_4 feed tanks. The high pressure N_2 at 1,035 kPa (150 psia) used to operate the pneumatic valves is supplied from a separate N_2 source. A single gas vent line is provided to vent the N_2 and H_2 product gases from the NGS. Both the N_2 product and the H_2 product gas are fed either to the gas chromatograph for gas analysis or to a soap bubble meter for flow rate measurement.

Power Supply. The TSA supplies 115 V and 230 V AC, 60 Hz, power to the NGS C/M I. No other power is required to operate the NGS.

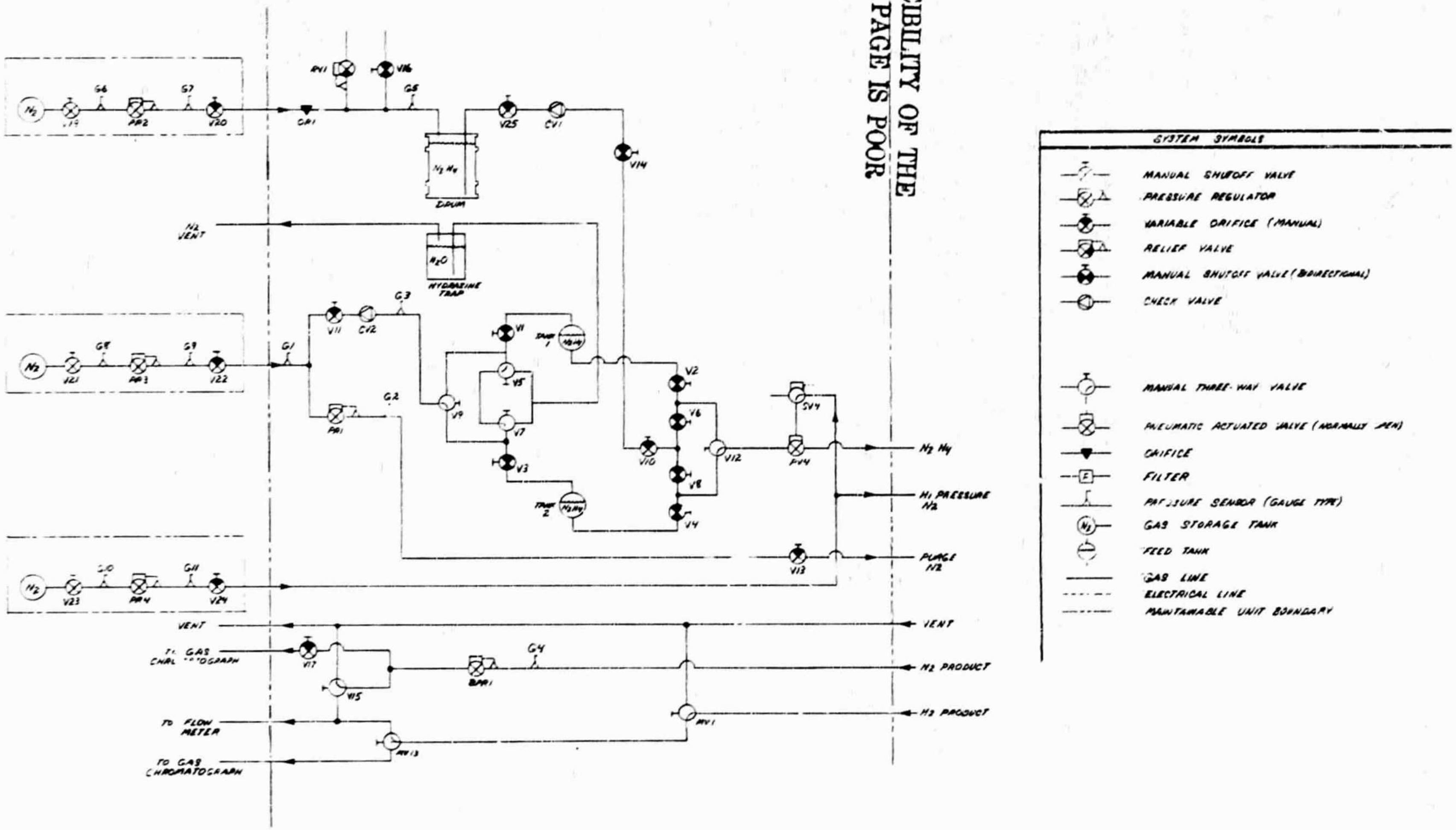


FIGURE 7 NGM TEST FACILITY TSA

Control/Monitor Instrumentation

Instrumentation is provided to: (1) control N_2H_4 Catalytic Dissociator temperature, (2) control Pd/Ag Separator temperature, (3) control solenoid valve and cooling fan operation, (4) provide automatic fail-safe shutdown when a critical parameter exceeds a preset level and (5) monitor system temperatures and pressures. Laboratory breadboard-style instrumentation was selected for maximum testing flexibility and the direct readout of the system parameters in engineering units.

Control Features. The following control features were incorporated:

1. Automatic fail-safe shutdown and N_2 purge initiated by excessive dissociator temperature and pressure, excessive Pd/Ag separator temperature and pressure, excessive N_2H_4 feed temperature, and low N_2 product pressure.

2. Startup accomplished by supplying power to the solenoid valves, cooling fan and the heater/temperature controllers. Shutdown is accomplished by removing power from these components.

3. Fan speed (voltage) manually set by a digital potentiometer.

4. Dissociator and separator stage temperatures maintained by individual, manually set temperature controllers.

The electrical power sources required to operate the instrumentation are 115 V AC, 60 Hz power, which is converted to 24 V DC within the test stand to run the instrumentation and 230 V AC, 60 Hz power for the NGM heaters.

Monitor Features. The following monitor features were incorporated:

1. Continuous monitoring and direct meter readouts for system temperatures.

2. Temperature shutdowns are signalled by T2 and T3.

3. Pressure shutdowns are signalled by PS1 and PS2.

Analysis Techniques

Conventional gas adsorption chromatography was used to measure the concentrations of the calibration gases, the N_2 product gas and the H_2 product gas. The gas chromatograph used for the gas analysis was calibrated over the concentration range listed below:

a. N_2 - 0 to 100%
b. H_2 - 0 to 100%
c. NH_3 - 0 to 10%

NGM Test Program

The test program consisted of individual stage checkout/parametric tests to verify individual stage performance, as in the case of the NH_3 dissociation and N_2H_4 dissociation stages, and to provide design data prior to final NGM fabrication, as was done for the separator stages.

Separator Stage Tests

The separator stage checkout/parametric tests were conducted using a single, four-loop, Pd/Ag tube having an outside diameter of 1.59 mm (0.063 in), a tube wall thickness of 0.076 mm (0.003 in) and a length of 2.4 m (8.0 ft).

Objective. The objective of the initial separator stage checkout/parametric testing was to verify the fabrication process and to generate design data to specify the number of tubes required in the final NGM configuration.

Procedure. Prior to installing the Pd/Ag tube into the NGM, the tube was pressure-checked to 2070 kPa (300 psia) to insure that there were no leaks in the tube or welded joints. The NGM was then assembled and the separator stage re-pressure checked at the same level once again to eliminate possible leaks from causing inaccuracy in the data generated. The NGM was then evacuated to remove all air and O_2 from the Pd/Ag tube and the NGM was repressurized with N_2. Three such evacuations and repressurizations with N_2 were used to insure no O_2 was present prior to allowing the H_2 mixture to enter the NGM. The process gas feed stream through the inside of the Pd/Ag tube was then purged with N_2 while the NGM was heated to 644 K (700 F). Certified premixed gas mixtures of N_2, H_2 and NH_3 were used for the test program. The premixed gas was introduced to the NGM after the temperature had stabilized at 644 K (700 F) Operating pressure and the H_2 recovery pressure for the NGM were then adjusted to the desired level. Data was taken starting approximately one hour after the certified gas mixtures were fed into the NGM. Each test condition was maintained for approximately six to eight hours during the course of a normal working day. Up to four data points were taken throughout the day to ensure steady-state operation. Following the testing, the NGM was purged with N_2 and several evacuations and repressurizations with N_2 performed prior to cooling the NGM. During the cooldown process, the NGM was again purged with N_2.

Test Results. The test conditions and test results for the three Pd/Ag checkout tests are shown in Table 4. The Stage 1 and 2 tests run on the test Pd/Ag tube configuration were successful. Data for the third stage however was questionable because of the low H_2 transfer and the high concentration of H_2 in the outlet gas stream. Previous tests on other separator configurations indicated that very low concentrations of H_2 in the product N_2 stream are possible. Further investigation of the test data and a subsequent pressure check indicated that there was a leak in the gasketing between the shell and tube side manifolds. The leak discovered only affected the third stage test since similar pressure checks were conducted following the two previous tests.

TABLE 4 Pd/Ag SEPARATOR CHECKOUT TEST RESULTS

Operating Conditions	Stage 1	Stage 2	Stage 3
N_2H_2 Feed			
Flow Rate, cm^3/min (scfm)	307.6 (0.0109)	204.2 (0.0072)	86.0 (0.0030)
Composition (by volume)			
N_2, %	67.2	73.8	96.0
H_2, %	32.8	24.0	4.0
NH_3, %	0	2.2	0
N_2 Product Pressure, kPa (psia)	1822 (264)	1725 (250)	1711 (248)
H_2 Permeate Pressure, kPa (psia)	167 (24.2)	0	0.6 (0.09)
Separation Stage Temperature, K (F)	644 (700)	644 (700)	644 (700)
Test Results			
H_2 Permeate Flow Rate, cm^3/min (scfm)	200.2 (0.0071)	46.2 (0.0016)	2.3 (0.0001)
Separation Efficiency, %	96.9	94.3	66.0

The number of Pd/Ag tubes required were calculated based on the test results. Since accurate data was not obtained on the third stage separator, the number of tubes required was calculated based on the data generated for the other two stages. For Stages 1, 2, and 3, 22, 14 and 7 tubes are required, respectively.

Ammonia Dissociation Tests

The NH_3 dissociation checkout/parametric tests were conducted using one of the three identical NH_3 dissociation stages. Each dissociator stage consists of two cylindrical columns packed with NH_3 dissociation catalyst. Each column has an inside diameter of 0.965 cm (0.380 in) and a length of 29.1 cm (11.5 in).

Objective. The objective of the NH_3 dissociator stage checkout/parametric tests were to verify the performance of each NH_3 dissociation stage and to demonstrate that low NH_3 concentrations in the product N_2 stream were obtainable through the NGM staging concept.

Procedure. Three tests were conducted to determine the efficiency of each individual NH_3 dissociation stage. The feed gas compositions were varied to simulate the feed for an end application NGM. Both the feed and product gases were analyzed by gas chromatography to determine their compositions. The test results and calculated efficiencies were then compared to projected values. Similar purging, preheating and cooldown procedures to those used in the separator test were used for the NH_3 dissociation tests.

Test Results. The test results for the NH_3 dissociator tests are shown in Table 5. The results are given according to stage number even though the feed gas compositions do not simulate the exact feed conditions projected. The efficiencies calculated from test results are comparable with or better than those projected for the NGM design as indicated in the table. The last NH_3 dissociation stage which determines the final NH_3 concentration in the product N_2 stream yielded 50 to 200 ppm NH_3 in N_2. The gas chromatographic analysis technique is inaccurate at low NH_3 concentrations. The product gas, however, was tested for NH_3 odor and a very faint NH_3 smell was detected. Since the odor threshold for NH_3 is approximately 50 ppm, the last stage testing indicated just slightly higher than 50 ppm NH_3 concentration. The feed gas stream used for the last stage testing contained approximately five times more NH_3 than is projected for the NGM. The testing completed, therefore, re-verifies the effectiveness of the staging concept used in the NGM.

Hydrazine Dissociation Test

The N_2H_4 dissociation checkout test was conducted using the N_2H_4 dissociator design that was fabricated for the NGM. The concentric annular housing of the N_2H_4 dissociation stage was packed with 13.5 g (0.030 lb) of catalyst.

Objective. The objective of the N_2H_4 dissociation stage test was to verify stage performance as measured by the NH_3 conversion efficiency and NH_3 concentration in the product gas streams.

TABLE 5 AMMONIA DISSOCIATOR CHECKOUT TEST RESULTS

Operating Conditions	Stage 1	Stage 2	Stage 3
Feed Gas Composition (by volume)			
N_2, %	95.19	74.40	99.02
H_2, %	0.45	23.00	0.51
NH_3, %	4.36	2.60	0.47
Product Gas Composition (by volume)			
N_2, %	97.87	75.78	99.43
H_2, %	2.00	24.00	0.55
NH_3, %	0.13	0.22	$\leq$0.02
N_2 Product Flow Rate, kg N_2/d (lb N_2/d)	4.51 (9.94)	3.38 (7.45)	3.69 (8.12)
Dissociator Temperature, K (F)	811 (1000)	813 (1004)	811 (1000)
Dissociator Pressure, kPa (psia)	1697 (246)	1704 (247)	1711 (248)
Test Results			
NH_3 Dissociation Efficiency			
Projected, %	80	80 to 95	95 to 98
Actual, %	96.9	91.3	$\geq$95.7

Procedure. The N_2H_4 dissociation stage testing was conducted at baseline operating conditions. Following an initial N_2 purge, the NGM was preheated and pressurized to 1725 kPa (250 psia). Hydrazine was introduced and the reactor temperature control to 997 K (1335 F). The product gases were analyzed by gas chromatography to determine the composition. The test results and calculated efficiency were then compared to projected values.

Test Results. The NH_3 conversion at the nominal operating conditions for the NGM was found to be approximately 98% which corresponds to an NH_3 concentration in a product gas stream of 0.9% by volume. The NH_3 conversion efficiency is much better than the 93% projected for the NGM design. The N_2 generation rate for the testing was 4.15 kg/d (9.15 lb/d) which is slightly higher than the design point of 3.63 kg/d (8.00 lb/d).

NITROGEN SUPPLY SUBSYSTEM DEVELOPMENT

The primary function of the NSS is to generate N_2 for cabin leakage makeup thereby controlling total cabin pressure. The NSS is an integratable subsystem within a central ARS. For an ARS based on Sabatier CO_2 reduction, the byproduct H_2 generated by the NSS is used to increase CO_2 reduction efficiency. The NSS can be divided into two parts consisting of those components located within the central ARS (i.e., the inhabited cabin), and the N_2H_4 storage and feed assembly which is located separately and most likely in common with other spacecraft N_2H_4 storage (i.e. an uninhabited cabin).

The objectives of the initial development activities described in this report were to (a) design and fabricate the N_2H_4 storage and feed mechanism as an assembly separate from the NSS components located within the ARS, (b) design and fabricate the peripheral mechanical and electrical components required to control and monitor subsystem performance for integration into a central ARS, and (c) design and fabricate the computer-based instrumentation hardware and software components required to interface the NSS with other ARS subsystems and controls. The following sections review the NSS design, summarize the Product Assurance activities completed and describe the TSA required for operating the NSS as part of an integrated ARS.

Subsystem Design

The NSS was designed as an integratable subsystem for a central ARS. Those components which would be redundant in another ARS subsystem have been eliminated in the NSS. In addition, certain functions that would be performed by the NSS for the entire central ARS have been included. The NSS consists of the N_2H_4 storage and feed mechanism, the NGM, the peripheral mechanical and electrical components required to control and monitor subsystem performance, and the advanced instrumentation required for the NSS to interface with other ARS subsystems and controls.

Design Specifications

The NSS was designed to deliver N_2 at a rate of 3.63 kg/d (8.00 lb/d) at pressures less than or equal to 1725 kPa (250 psia). The design specifications for the NSS are listed in Table 6.

TABLE 6 NITROGEN SUPPLY SUBSYSTEM DESIGN SPECIFICATIONS

Leakage Data	
Air Leakage Rate, kg/d (lb/d)	4.74 (10.43)
N_2 Leakage Rate, kg/d (lb/d)	3.63 (8.00)
O_2 Leakage Rate, kg/d (lb/d)	1.10 (2.43)
Cabin Atmosphere Data	
Operational Gravity, m/s^2 (G)	0 to 9.8 (0 to 1)
Total Pressure, kPa (psia)	101.4 (14.7)
O_2 Partial Pressure, kPa (psia)	21.4 (3.1)
Diluent	N_2
Volume	
Initial, m^3 (ft^3)	439 (15,500)
Growth, m^3 (ft^3)	960 (33,900)
Ventilation Rate	
Minimum, cm/s (ft/min)	7.6 (15)
Maximum, cm/s (ft/min)	20.3 (40)
H_2 Concentration, Volume %	0.2
NH_3 Concentration, Volume %	5.0×10^{-3}
Temperature, K (F)	291 to 297 (65 to 75)
Surface Temperature Guidelines, K (F)	≤322 (120)
Acoustical Guidelines	NC-65

Design Features

The overall goal of the design effort was to design an NSS as an integrated subsystem within a central ARS. The design features incorporated, therefore, were selected based on both subsystem and integrated system design requirements. The following is a list of the major design features incorporated.

1. The subsystem components were developed for assembly within an integrated ARS as opposed to a separate subsystem interface.
2. A separate N_2H_4 storage and feed mechanism assembly was designed to simulate that portion of the NSS that would be located outside the inhabitable cabin.
3. The byproduct H_2 generated can be used by a Sabatier reactor for CO_2 reduction.
4. The NSS has self-contained, fully automated controls.
5. Control and monitoring functions are provided by computer-based instrumentation utilizing software programming techniques.
6. Four steady-state operating modes were incorporated.
7. The mode transition sequences were integrated into the sequencing required for an integrated ARS.
8. Manual overrides and controls have been included for off-design testing.
9. Redundant N_2H_4 storage tanks were developed to simulate the controls required to switch tanks as required in actual flight application.
10. Redundant automatic shutoff valves were used on the N_2H_4 feed line for projected flight safety and maintenance requirements.
11. All materials of construction used are compatible with their environment.

Subsystem Operation

Figure 8 is a block diagram of the NSS. High pressure N_2 at approximately 2070 kPa (300 psia) is used to pressurize the N_2H_4 storage tanks. Hydrazine is forced from the tanks through a flow control which controls the N_2H_4 feed rate to the NGM by adjusting the feed pressure to the tanks. The N_2 and H_2 product streams are cooled in air heat exchangers prior to exiting the subsystem. The N_2 product pressure is controlled at 1725 kPa (250 psia) by a backpressure regulator. The H_2 vent-to-vacuum stream from the second and third H_2 separation stages in the NGM is not cooled prior to exiting the subsystem. The absolute mass flow rate and heat capacity in the stream is very small and the gas stream will reach ambient temperature in just the length of tubing required to vent the stream from the subsystem.

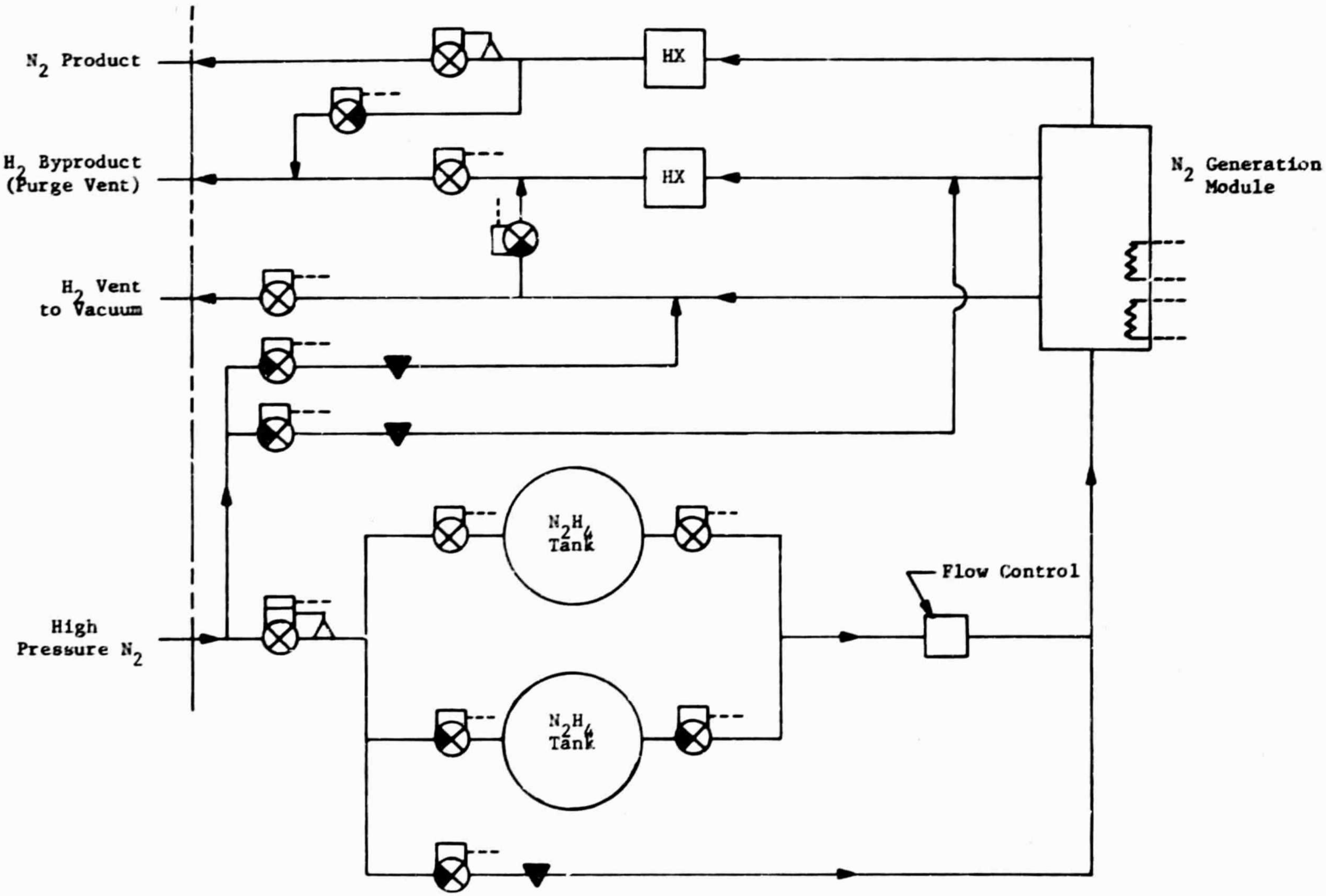


FIGURE 8 NITROGEN SUPPLY SUBSYSTEM BLOCK DIAGRAM

Solenoid valves are provided on the two N_2H_4 tanks to allow continuous operation of the NSS. One tank is always operating while the other tank remains in standby. As the first tank is emptied, the second tank is switched on-line and the first tank is isolated for refilling.

Solenoid valves and flow control orifices are used to distribute the high pressure N_2 for purging the three process gas streams. Solenoid valves on the H_2 vent-to-vacuum and N_2 product streams allow all purge gas to be vented through the H_2 byproduct stream which would be connected to the CRS. As part of an integrated ARS, the CRS would handle the purge vent for all ARS subsystems to prevent duplication of valving required to exhaust purge gas to space vacuum. The H_2 vent-to-vacuum requirements would be handled similarly as part of the ARS so duplication is not required in the NSS.

The detailed schematic of the NSS, presented in Figure 9, shows the specific valves and sensors that will be used in the NSS. The N_2 feed to the supply tanks is controlled using a motor-driven regulator (V30) and a closed-loop feedback control from flow control Q8. The flow control monitors the pressure drop across a fixed orifice and automatically adjusts the feed tank pressure to give the desired flow rate as measured by differential pressure across the orifice.

The N_2H_4 storage tanks are shown as being located in a nonhabitable compartment of the spacecraft. Hydrazine stored on-board a spacecraft would be fed to the NSS from outside the inhabited cabin atmosphere.

Manual valves (MV2 through MV6) are provided to refill the tanks since each supply tank was sized to last approximately five days. Solenoid valves V32 through V35 determine which tank is on-line. The control instrumentation automatically alerts the operator when a tank needs to be refilled and automatically switches in the reserve tank. Pressure sensors and orifices are used to measure the amount of N_2H_4 in the reserve tank prior to switching to the reserve tank. This prevents switching in an N_2H_4 tank which has not been filled. The concept works on the principal of timing how long it takes to pressurize the tanks with N_2 pressure through a fixed resistance flow orifice. A very short pressurization time (less than 0.1 s) would indicate that the tanks were relatively full whereas a longer pressurization period (up to 10 s) would indicate a lower level of N_2H_4 in the tanks.

Redundant solenoid valve V28 and manual valves MV4 and MV7 are used as a safety precaution to ensure that during a shutdown the N_2H_4 feed stream is disconnected from the NGM both automatically and manually. Nitrogen purge is provided through solenoid valves V28, V29 and V31. Solenoid valve V31 also serves the dual purpose of prepressurizing the NGM prior to startup. Various pressure, temperature and flow sensors are located throughout the subsystem for sequencing control and fault isolation and detection.

The N_2 generated by the NSS is vented to the cabin for cabin leakage makeup. The high pressure N_2 stream is also used for pressurization purposes in other ARS subsystems. The NSS serves as the interface with spacecraft high pressure N_2 that is used to purge other ARS subsystems. The spacecraft N_2 supply, therefore, interfaces with the NSS which interfaces with other subsystems requiring N_2 purge.

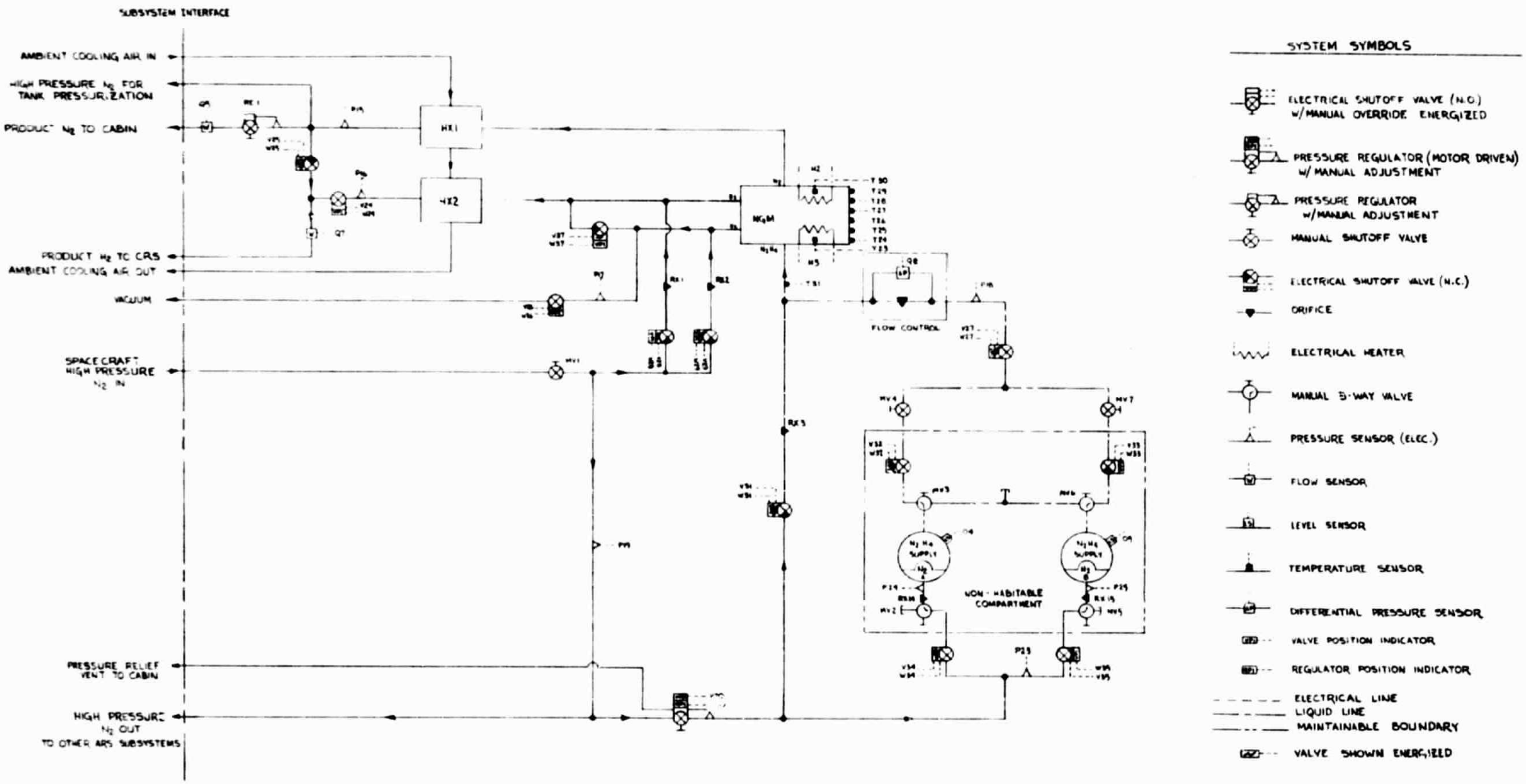


FIGURE 9 NITROGEN SUPPLY SUBSYSTFM SCHEMATIC

Mechanical Hardware Description

Table 7 lists the NSS mechanical components, including the number required, weight, volume and power for each component. The NGM and the N_2H_4 storage tanks were developed specially for the program. All other components were selected "off-the-shelf" to reduce development costs. All components do, however, meet the materials compatibility specifications required for the NSS. All functions, as presently projected for the NSS as part of a central ARS have been included. The sensors located throughout the system are used to control NSS operation and provide protective shutdown and trend analysis monitoring. The temperature sensors and heaters located within the NGM are considered as part of the NGM component and are therefore not called out separately in Table 7.

Figure 10 shows the N_2H_4 storage and feed assembly. The components contained within this assembly were identified in the subsystem schematic (see Figure 9) by the maintainable boundary for the nonhabitable compartment. All other components including the NGM are located within the central ARS.

Control and Monitor Instrumentation

Computer-based C/M I that was developed for the NSS is integratable with a central ARS C/M I. The central ARS C/M I controls and monitors all ARS subsystems.

The function of the C/M I is to provide:

1. Automatic mode control and mode transitions.

2. Automatic shutdown provisions for self-protection.

3. Provisions for monitoring critical parameters.

4. An interface with TSA instrumentation.

The NSS has five operating modes: Shutdown, Normal, Standby, Purge and Unpowered. The five modes and the allowable mode transitions are shown in Figure 11. There are eight allowable mode transitions that can be programmed or commanded during NSS operation. In the event of a power failure, however, all modes can transition to the unpowered mode during which time all actuators and valves will go to the de-energized position. Upon repowering the NSS, all actuators are put in the shutdown position.

Subsystem Controls

The preliminary control function of the NSS C/M I is to control mode transitions and steady-state operation. Table 8 lists the actuator conditions for the five steady-state modes.

TABLE 7 NSS MECHANICAL COMPONENTS SUMMARY

Component	Number Required	Weight,[a] kg (lb)	Volume,[b] dm^3 (in^3)	Power,[c] W
Module, N_2 Generation	1	61.3 (135.0)	22.4 (1365)	150
Heat Exchanger	2	0.1 (0.2)	0.1 (5)	-
Valve (W/VPI), Shutoff, Electrical	12	0.6 (1.3)	0.2 (11)	11
Valve, Shutoff, Manual	3	0.1 (0.3)	0.2 (10)	-
Valve, Three-way, Manual	4	0.1 (0.3)	0.2 (10)	-
Sensor, Pressure	8	0.6 (1.3)	0.4 (24)	5
Control, Flow	1	0.7 (1.5)	1.2 (75)	5
Sensor, Flow	2	1.1 (2.4)	0.7 (44)	5
Orifice	5	0.05 (0.1)	0.0 (0)	-
Regulator, Backpressure	1	1.2 (2.6)	0.8 (49)	-
Regulator, Pressure, Motor Driven	1	1.5 (3.4)	0.9 (54)	-
Tank, Storage N_2H_4	2	12.3 (27)[d]	18.9 (1150)	-

(a) Basic System Weight = 104.6 kg (230.3 Lb)
(b) Basic System Volume = 71.0 dm^3 (2.5 ft^3)
(c) Basic System Power = 337 W
(d) Does not include expendible N_2H_4 weight

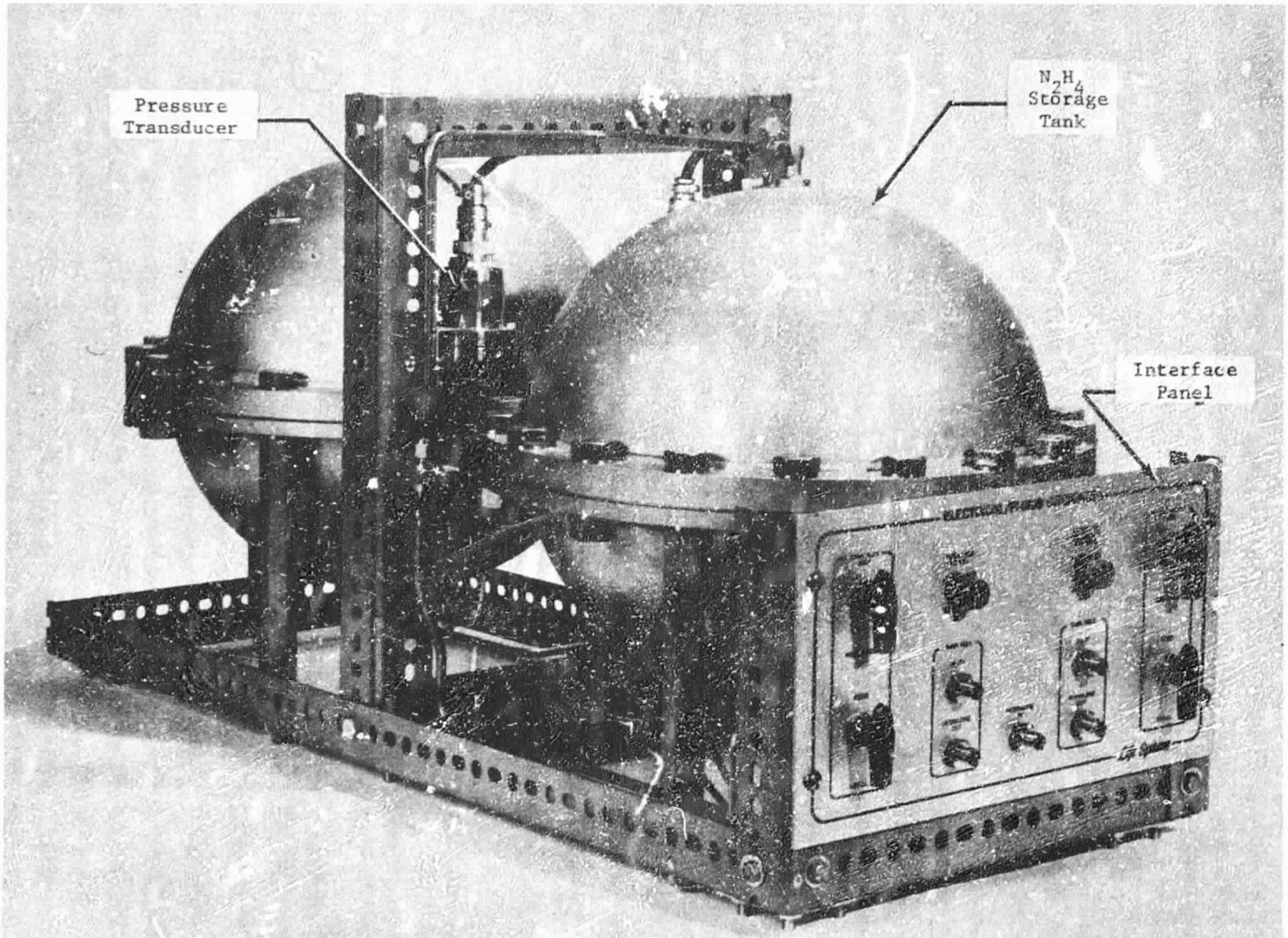
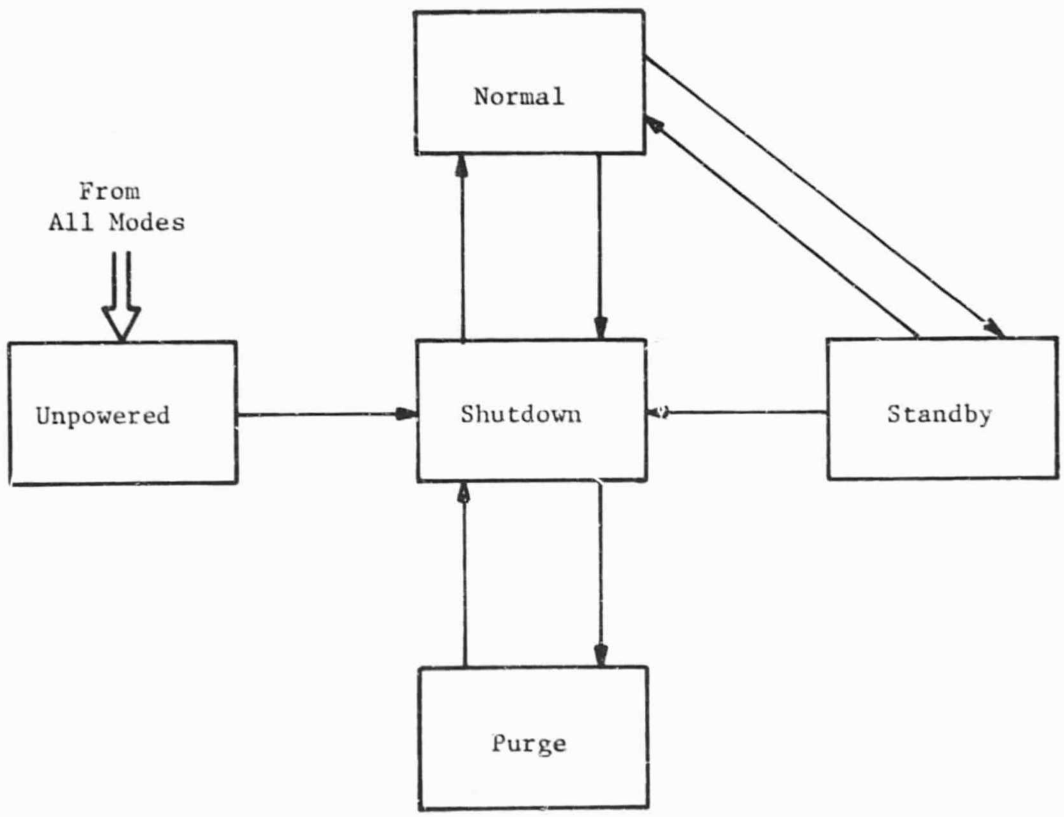


FIGURE 10 HYDRAZINE STORAGE AND FEED ASSMEBLY



- 5 Modes
- 8 Allowable, Programmable Mode Transitions

FIGURE 11 NSS OPERATING MODES AND ALLOWABLE TRANSITIONS

TABLE 8 ACTUATOR CONDITIONS FOR NSS OPERATING MODES

	Shutdown	Normal	Standby	Purge
V24	0[a]	0	0	0
V25	0	X[b]	X	0
V26	0	X	X	0
V27	0	X	X	0
V28	X	X	X	0
V29	X	X	X	0
V30	0	X	X	0
V31	X	X	X	0
V32	0	X[c]	X[c]	0
V33	0	0[c]	0[c]	0
V34	0	X	X	0
V35	0	X	X	0
V37	0	X	X	0
H2	0	X	X	0
H3	0	X	X	0

(a) 0 indicates actuator de-energized
(b) X indicates actuator energized
(c) Condition depends on which N_2H_4 tank is used

In addition to steady-state mode control and transition sequences, the NSS C/M I contains two temperature controls and the N_2H_4 feed control. Temperature control is achieved using heaters H2 and H3 and sensors T23 and T30, respectively (see Figure 9). The N_2H_4 feed control uses flow sensor Q8 and adjusts the motor-driven pressure regulator (V30) which feeds high pressure N_2 to the N_2H_4 storage tanks to give the desired N_2H_4 flow rate. The feed control also determines which N_2H_4 tank will be used during operation and changes tanks as required to maintain a constant N_2H_4 flow to the NGM. The absolute pressure level of the NGM is set using a manual pressure regulator (RE1) and is not automatically adjusted during normal NSS operation.

Subsystem Monitoring

Various temperature, flow and pressure sensors are located throughout the NSS to protect the subsystem by initiating a shutdown should a critical parameter exceed a preset level. The NSS sensor list is presented in Table 9. The table shows the monitoring range for each sensor and the shutdown point on critical sensors. The flow sensors for the NSS are used only for monitoring and have no shutdown capability as indicated in the table. Additional sensors which are not called out as part of the NSS are the combustible gas sensors located near the ARS subsystems and a combustible gas sensor located in the line that vents the N_2 and O_2 generated by the O_2 Generation Subsystem (OGS) from an ARS into the cabin. These two sensors protect against possible internal/external H_2 leakage and failure of the NGM to deliver high purity N_2 to the cabin. These sensors were not listed in Table 9 since they are considered part of another ARS subsystem but could shut down the NSS.

Product Assurance Program

The Product Assurance Program established, implemented and maintained throughout the development of the NSS included considerations for quality assurance, reliability, maintainability, safety, materials control and configuration management. The following sections summarize the activities completed in each area.

Quality Assurance Program

The objective of the Quality Assurance Program was to search out quality weaknesses and provide appropriate corrective actions. Quality assurance considerations were included during the NSS design, engineering evaluation and fabrication activities. All vendor-supplied parts were checked out when received to ensure adherance to design specifications prior to assembly into the NSS. Only minor quality deficiencies in vendor-supplied parts were identified during the program and all were resolved prior to incorporation into the NSS.

Reliability Program

The objective of the Reliability Program was to include reliability considerations into the design of the NSS. A Single Point Failure Analysis (SPFA) and a Failure Modes and Effects Analysis (FMEA) was completed for the NSS. As a result of the analyses, redundant shutoff valves and dual N_2H_4 storage tanks

TABLE 9 NSS SENSOR LIST

Type	Sensor Number[a]	Range[b]	Shutdown Point[b]
Pressure	P15	0 to 2070 (0 to 300)	2070 (300)
Pressure	P16	0 to 345 (0 to 50)	345 (50)
Pressure	P17	0 to 173 (0 to 25)	173 (25)
Pressure	P18	0 to 2070 (0 to 300)	2070 (300)
Pressure	P19	0 to 3450 (0 to 500)	3450 (500)
Pressure	P23	0 to 2070 (0 to 300)	2070 (300)
Pressure	P24	0 to 2070 (0 to 300)	2070 (300)
Pressure	P25	0 to 2070 (0 to 300)	2070 (300)
Temperature	T23	294 to 700 (70 to 800)	N/A
Temperature	T24 to T26	294 to 700 (70 to 800)	700 (800)
Temperature	T27 to T29	294 to 1089 (70 to 1500)	1089 (1500)
Temperature	T30	294 to 1089 (70 to 1500)	N/A
Temperature	T31	294 to 311 (70 to 100)	311 (100)
Flow	Q5	0 to 5000	N/A
Flow	Q7	0 to 5000	N/A
Flow	Q8	0 to 5	N/A

(a) See Figure 9 for sensor location.
(b) Pressures given in kPa (psia), temperatures in K (F) and flow rates in cc/min.

were incorporated into the NSS design. A review of literature for projected N_2H_4 storage and handling techniques resulted in the selection of locating the N_2H_4 storage tanks in the nonhabitable compartment section of a spacecraft. All liquid N_2H_4-carrying lines were then considered nonmaintainable and required redundant valving to meet reliability requirements.

Maintainability Program

The objective of the Maintainability Program was to consider "hands off" operation as a design goal with routine maintenance required during testing. A line replaceable or flight replaceable component concept was selected to maintain those components requiring maintenance to achieve the desired subsystem reliability goal during any continuous 180-day operational period. All subsystem components, with the exception of those located in the liquid N_2H_4 lines, were considered line replaceable components.

Safety Program

An effort was made during the design of the NSS to consider if operation of the subsystem is consistent with flight safety requirements. All N_2H_4 handling requirements and safety considerations as established during previous programs were implemented during the present NSS development. In addition to the N_2H_4 safety requirements, the following safety features were also incorporated:

1. A single failure in one component will not cause successive failures in other components.

2. The subsystem is designed so that operation and maintenance can be performed without hazard to personnel.

3. As a safety precaution against the possibility of external leakage of N_2H_4 and H_2 from all N_2H_4 or H_2-carrying lines, the design uses welded plumbing wherever feasible.

4. Provisions have been made so that circuit breakers are incorporated (in TSA) to protect electrical equipment from unexpected high currents.

5. Electrical connectors, plugs and receptacles are positively keyed to prevent incorrect mating with other accessible connectors, plugs or receptacles

6. In all connections, the hot electrical connector is the female socket.

7. Electrical circuits are not routed through adjacent pins of an electrical connector if a short between them will constitute a failure which could cause a serious problem.

8. The fluid and electrical interface panel has been clearly labeled to prevent incorrect connection of fluid and electrical lines.

Materials Control Program

The objective of the Materials Control Program was to provide assurance that the NSS will not preclude the efficient application of a more detailed subsystem material control program during follow-on efforts. Special consideration was given to compatibility with N_2H_4. All metallic and nonmetallic materials used in N_2H_4-carrying lines were screened for compatibility and were only accepted if they met all compatibility criteria. All metallic and nonmetallic materials selected are compatible with their environment and scheduled maintenance was not selected as a method of working around possible corrosion or materials compatibility problems.

Configuration Management Program

The objective of the Configuration Management Program was to insure that the NSS was integratable as part of a central ARS. Activities in this area were limited to supplying NSS interface requirements and reviewing interface requirements of other central ARS subsystems.

NSS Test Support Accessories

Figure 12 shows the NSS TSA schematic required for operation. The primary function of the TSA is to supply N_2H_4 to the storage tanks located in the NSS. Bulk N_2H_4 is stored in a 0.21 m (55 gal) drum which cannot be pressurized over 138 kPa (20 psia). In order to transfer the N_2H_4 from the drum located in the N_2H_4 storage area to the tanks located in the NSS requires greater than 138 kPa (20 psia) pressure. An intermediate higher pressure transfer tank is used for this purpose. After refilling the NSS N_2H_4 tanks, the line connecting the transfer tank which is located by the storage drum and the TSA located at the NSS is purged with N_2 to remove any N_2H_4 in the lines as a safety precaution.

In addition to N_2H_4 tank refilling components, the TSA supplies purge N_2 and distributes the purge N_2 for use in other ARS subsystems.

CONCLUSIONS

The following conclusions were reached:

1. The integration of multiple H_2 separation, and N_2H_4 and NH_3 dissociation stages into an NGM is feasible. The design completed successfully integrates seven dissociation/separation stages into a single package to effectively use the heat generated in the N_2H_4 dissociation process to heat the other stages.

2. An NSS can be designed and integrated into a central ARS. The NSS design completed is fully integratable with an ARS and has been sized to deliver 3.63 kg/d (8.00 lb/day) of N_2 at greater than or equal to 1725 kPa (250 psia). This N_2 generation rate corresponds to a six-person spacecraft application.

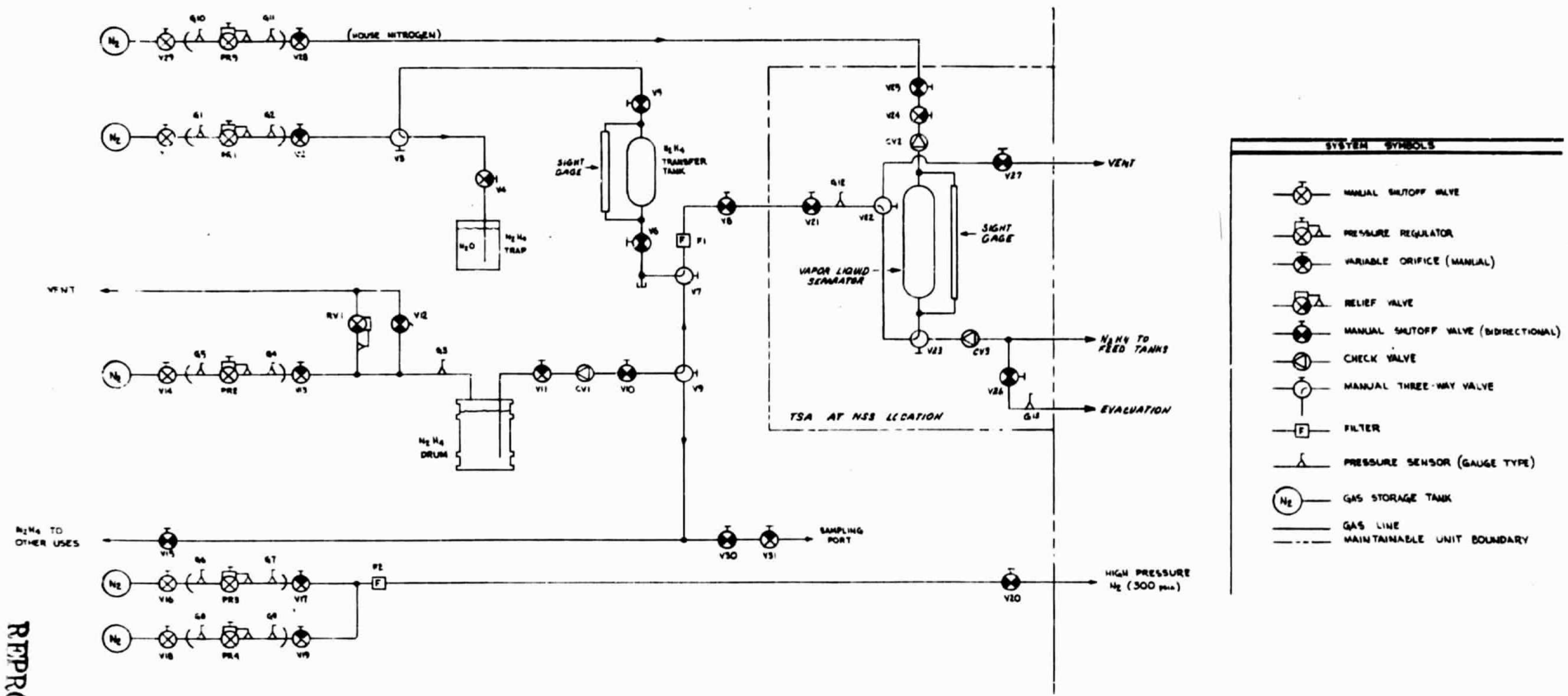


FIGURE 12 NSS TEST SUPPORT ACCESSORIES

3. The NGM staging technique is an effective method of delivering high purity N_2 for spacecraft leakage makeup. Data gathered on an NH_3 dissociation stage verified that low NH_3 concentrations (50 ppm) are attainable using the NGM.

4. An improved NGM sealing technique is required. The flat graphite gasket design incorporated did not provide reproducible bubble-tight seals required for future testing.

RECOMMENDATIONS

The following recommendations are a direct result of the work completed:

1. The NSS should be tested as an integratable subsystem within a central ARS to determine its performance as a function of N_2 generation rate, NGM operating temperature and N_2 delivery pressure.

2. An improved NGM sealing technique should be developed and retrofitted into the present NGM prior to further testing. The NGM should then be individually tested as a component to ensure reliable, reproducible performance prior to incorporation into the NSS for extensive testing.

3. Based on the test results gathered for the NSS, an advanced NGM should be designed, developed, fabricated, assembled and tested. The objective of the development activities would be to reduce NGM weight and power required (a passive thermal design is desired such that the heat generated during N_2H_4 dissociation is sufficient to maintain the NGM at temperature without thermal controls). A 50% weight reduction is presently projected as a reasonable goal.

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